



Adjoint-based Mesh Adaptation for the Sonic Boom Signature Loudness

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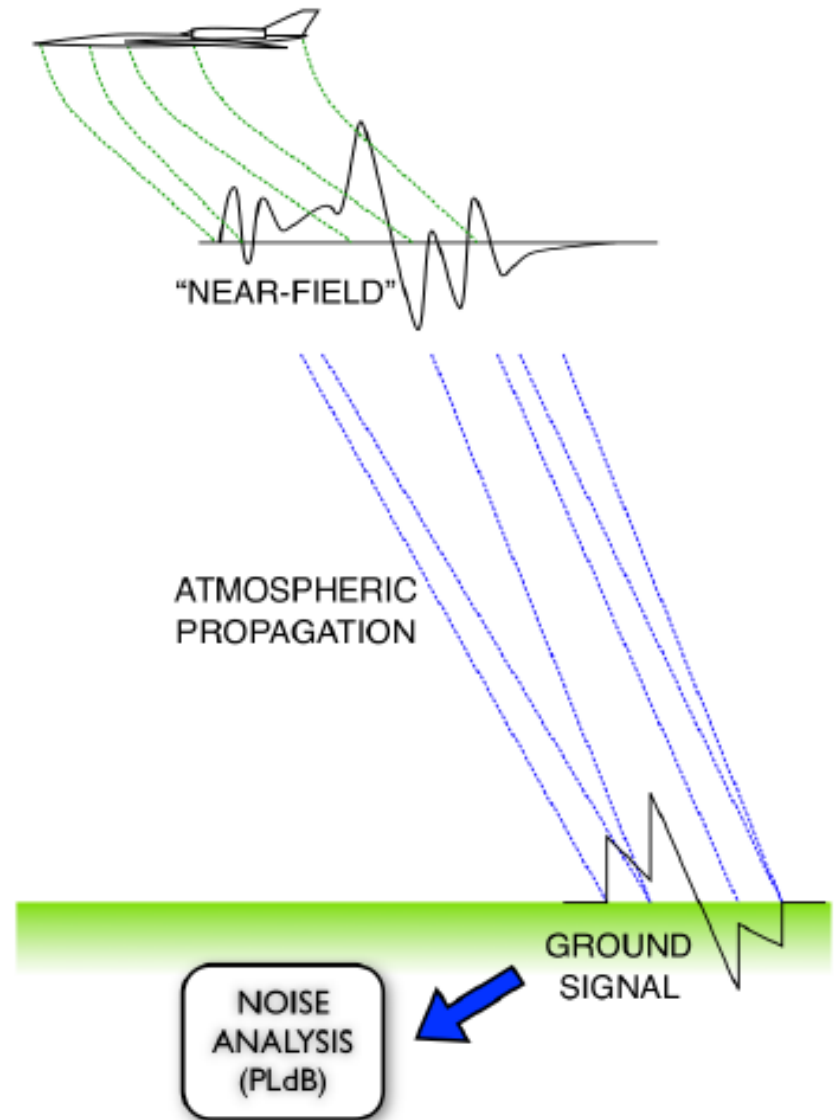


Outline

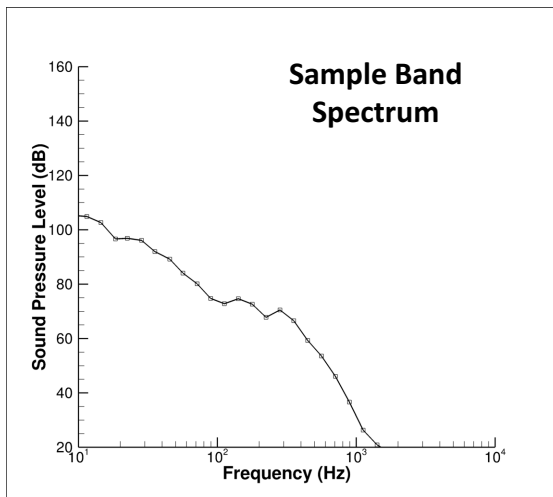
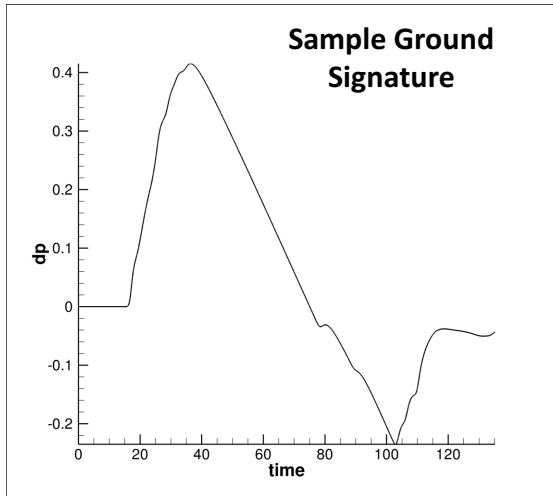
- Introduction and Motivation
- Background
 - FUN3D
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Introduction and Motivation

- Commercial supersonic flight overland requires overcoming sonic boom annoyance
- Sonic boom prediction involves:
 - CFD simulation (Inviscid or viscous) near the aircraft to generate an off-body pressure waveform termed as “near-field”
 - Atmospheric propagation where the pressure disturbances are modeled as they reach the ground
 - Possibly under prevailing atmospheric conditions including winds
 - Standard atmosphere assumed as U.S. Standard Atmosphere (1976) with guidance on humidity profiles
 - Noise analysis
 - Frequency spectrum (1/3-octave frequency bands)
 - Multiple metrics: Perceived Level (PL) and A-weighted Sound Exposure Level (ASEL) is used in this study

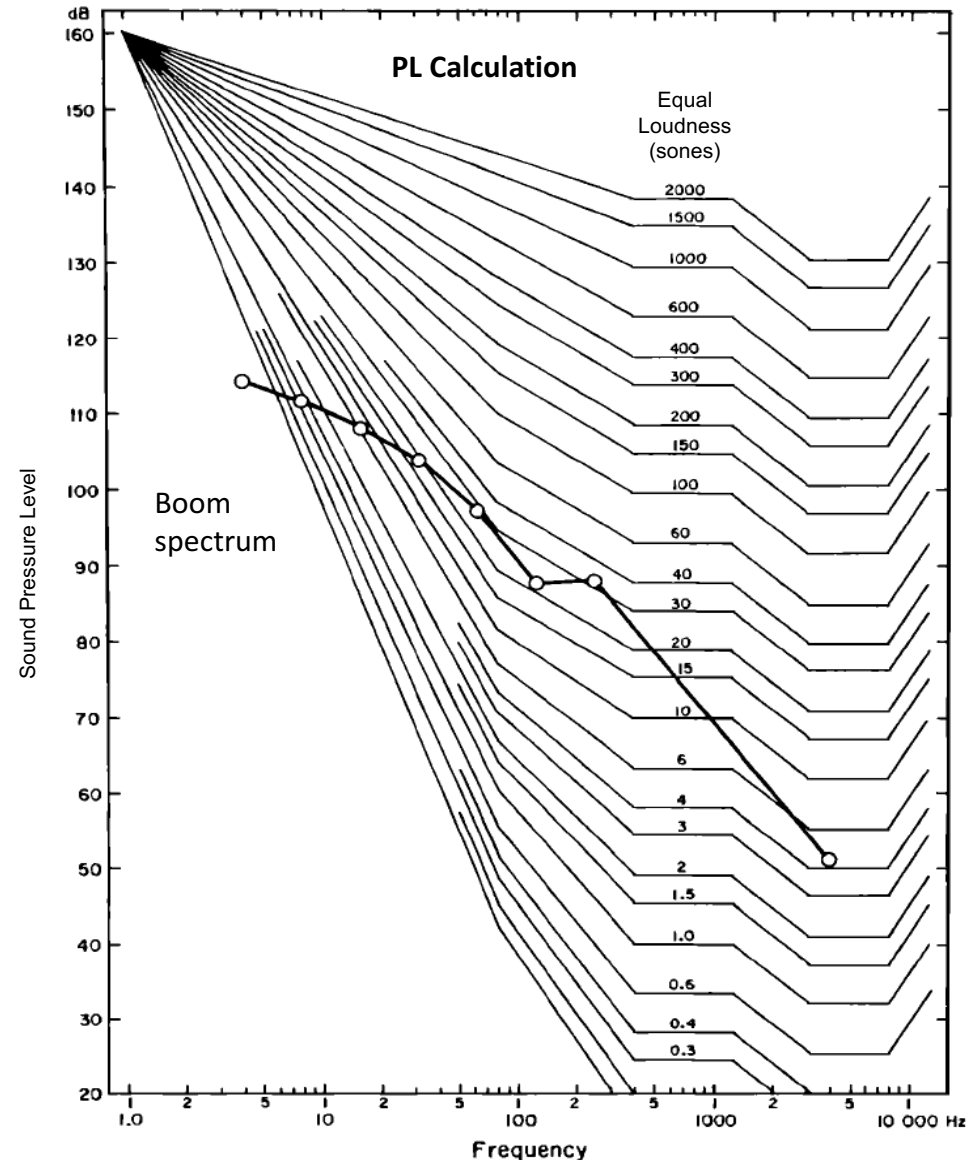


Introduction and Motivation



$$S_t = S_m + F(\Sigma S - S_m)$$

$$PL = 32 + 9 \log_2(S_t)$$

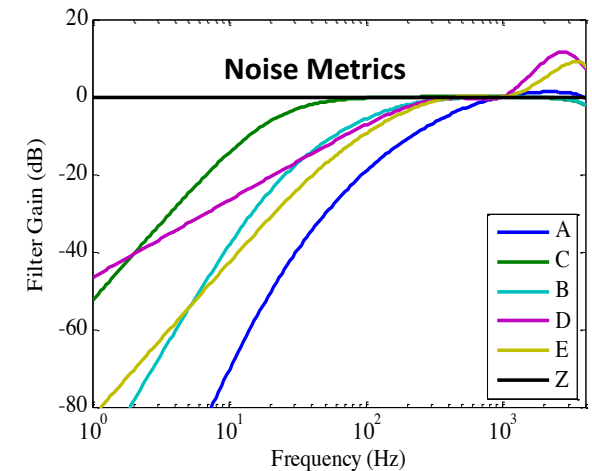


S. S. Stevens. Perceived level of noise by Mark VII and decibels (E). J. Acoust. Soc. Am., 51(2):575–601, 1972.

K. P. Shepherd and B. M. Sullivan. A loudness calculation procedure applied to shaped sonic booms. NASA Technical Report TP-3134, 1991.

Introduction and Motivation

- Perceived level (PL) is the generally accepted quantitative measure of sonic boom
 - Decibels are logarithmic
 - CFD mesh and atmospheric propagation sampling requirements increase as signals get quieter
 - Specialized boom meshes (INFLATE¹, MCAP², Boom Grid³) may or may not be sufficient
 - Adjoint-based mesh adaptation offers a way to generate suitable meshes for the output being optimized
- PL metric not amenable to differentiation
- A-weighted Sound Exposure Level (ASEL) has been shown to be well correlated⁴ with PL for outdoor sonic booms



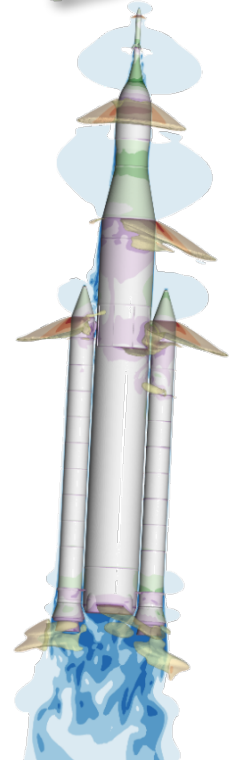
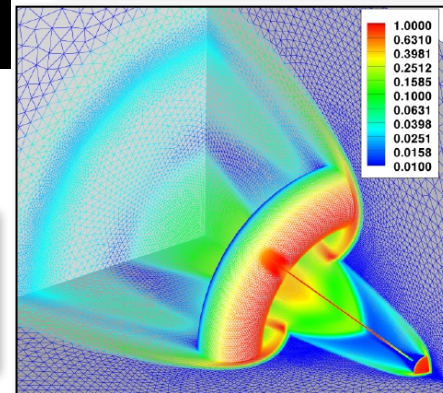
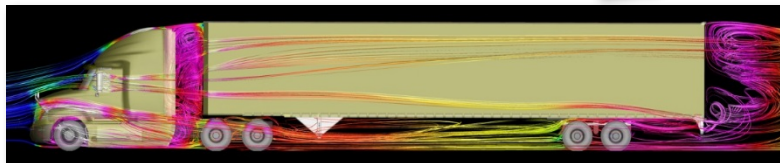
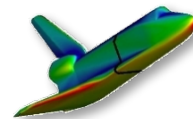
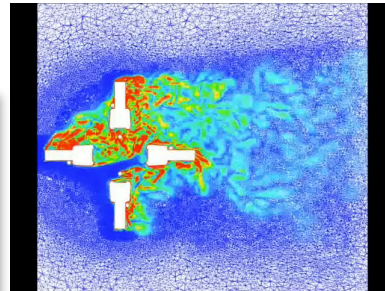
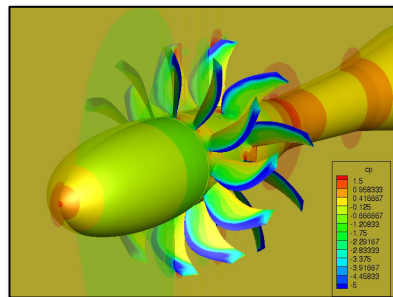
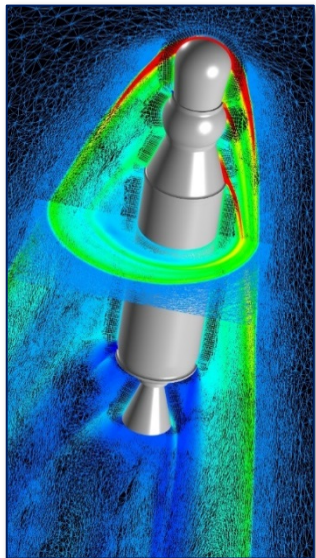
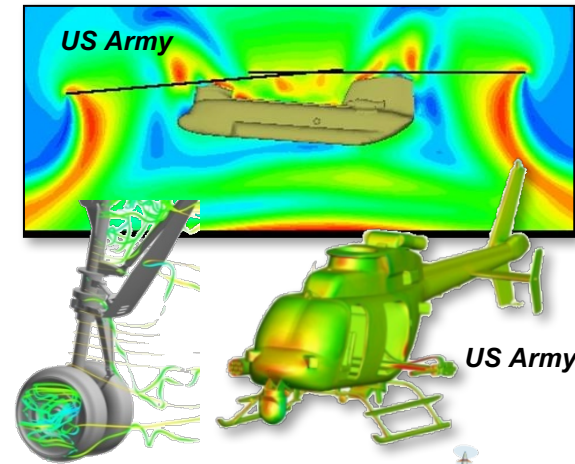
¹Michael A. Park, Richard L. Campbell, et al. "Specialized CFD Grid Generation Methods for Near-Field Sonic Boom Prediction", AIAA 2014-0115

²Cliff, S. E., Elmiligui, A. A., et al. , "Evaluation of Refined Tetrahedral Meshes with Projected, Stretched, and Sheared Prism Layers for Sonic Boom Analysis," AIAA 2011-3338

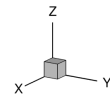
³Nayani, S. N. and Campbell, R. L., "Evaluation of Grid Modification Methods for On- and Off-Track Sonic Boom Analysis," AIAA 2013-798

⁴Loubeau, A., Naka, Y., Cook, B. G., Sparrow, V. W., and Morgenstern, J. M., "A New Evaluation of Noise Metrics for Sonic Booms Using Existing Data," 2nd International Sonic Boom Forum, 20th International Symposium on Nonlinear Acoustics, July 2015.

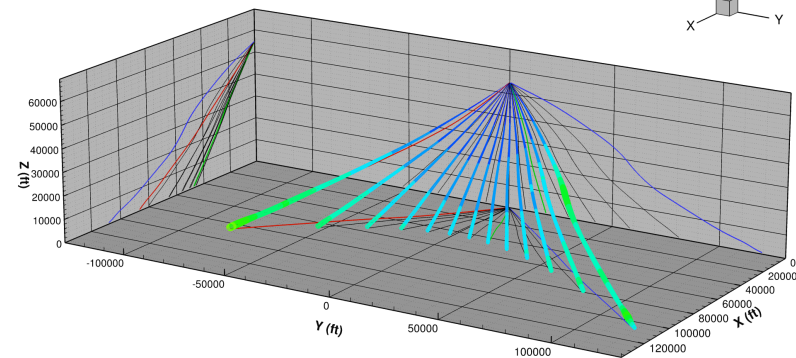
- Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, CC, etc.
- Constrained / multipoint adjoint-based design, mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Capabilities fully integrated, online documentation, training videos, tutorials



sBOOM

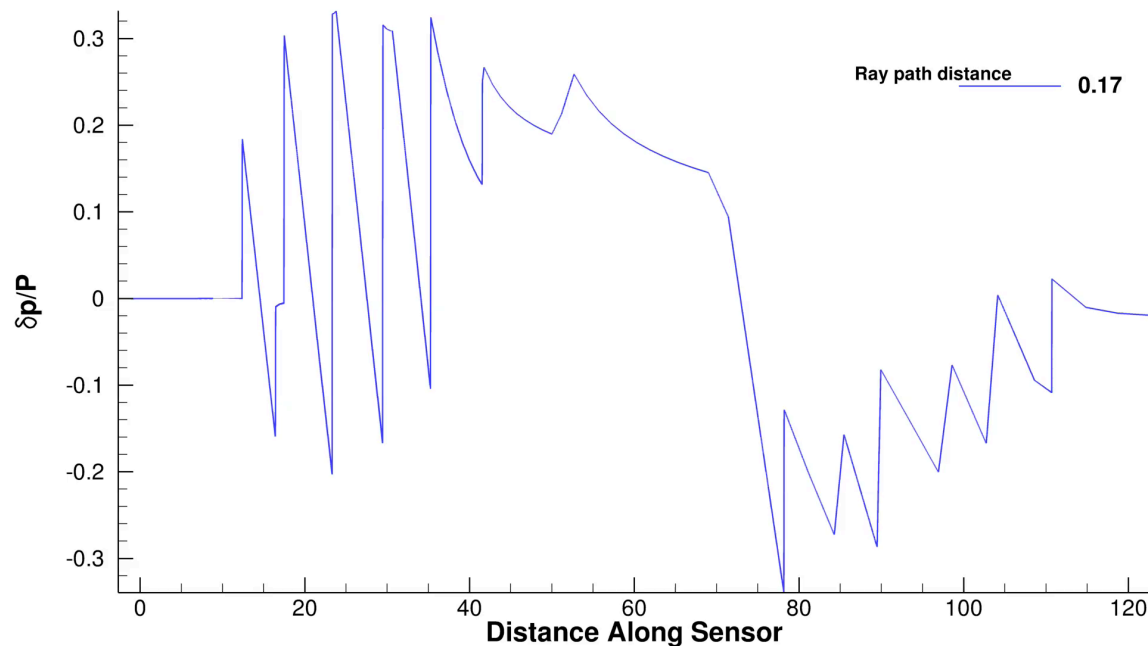


- Propagation based on lossy Burgers equation
- **Features**
 - Under-track, off-track signatures, Horizontally stratified winds, Acceleration, turn-rates, climb-rates
- **Adjoint-based design capability**
 - Near-field dp/p matching
 - Ground loudness optimization/ Target/ EA matching
 - Target equivalent area generation
 - Atmospheric sensitivities



Recent sBOOM enhancements

- Boom focusing calculations, interfacing with non-linear Tricomi solver



sBOOM is under active development. Contact Sriram.Rallabhandi@nasa.gov or Lori.Ozorowski@nasa.gov to get a copy of sBOOM

FUN3D-sBOOM Coupling

- Input to sBOOM is represented by a transformation (\mathbf{T}) that maps CFD solution to the desired pressure distribution

$$p_0 = \mathbf{T}(\mathbf{Q}, \mathbf{X})$$

- Lagrangian

$$\mathbf{L}(\mathbf{D}, \mathbf{Q}, \mathbf{X}, \boldsymbol{\Lambda}_f, \boldsymbol{\Lambda}_g, \boldsymbol{\Lambda}_b) = J + [\boldsymbol{\Lambda}_g]^T \mathbf{G} + [\boldsymbol{\Lambda}_f]^T \mathbf{R} + [\boldsymbol{\Lambda}_b]^T (p_0 - \mathbf{T})$$

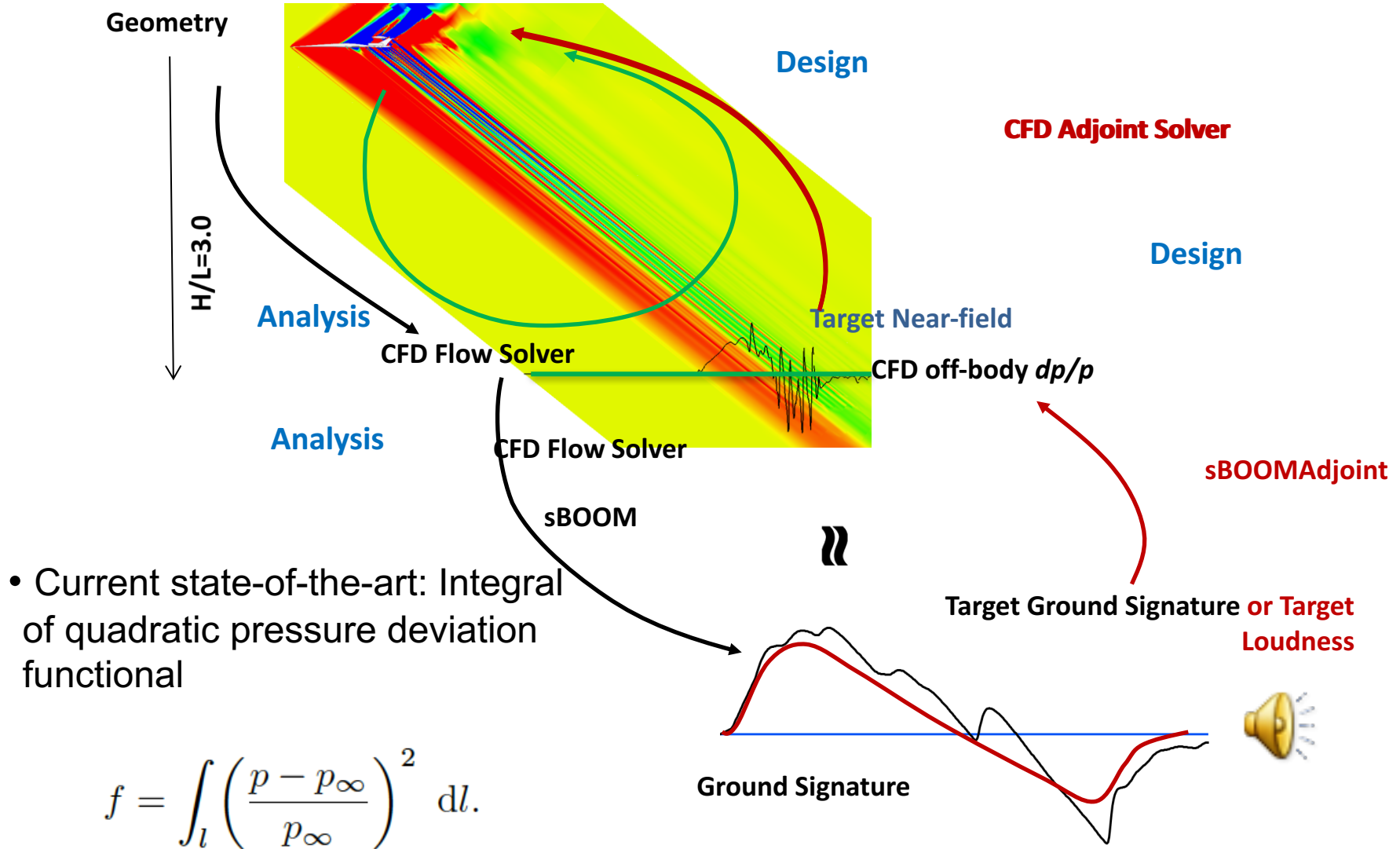
- System of adjoint equations

$$\begin{aligned} \left[\frac{dJ}{dp_0} \right]^T + \boldsymbol{\Lambda}_b &= 0, \\ \left[\frac{\partial \mathbf{R}}{\partial \mathbf{Q}} \right]^T \boldsymbol{\Lambda}_f - \left[\frac{\partial \mathbf{T}}{\partial \mathbf{Q}} \right]^T \boldsymbol{\Lambda}_b &= 0, \\ \left[\frac{\partial \mathbf{G}}{\partial \mathbf{X}} \right]^T \boldsymbol{\Lambda}_g + \left[\frac{\partial \mathbf{R}}{\partial \mathbf{X}} \right]^T \boldsymbol{\Lambda}_f - \left[\frac{\partial \mathbf{T}}{\partial \mathbf{X}} \right]^T \boldsymbol{\Lambda}_b &= 0. \end{aligned}$$

- Desired sensitivity derivatives

$$\frac{\partial \mathbf{L}}{\partial \mathbf{D}} = [\boldsymbol{\Lambda}_g]^T \frac{\partial \mathbf{G}}{\partial \mathbf{D}} + [\boldsymbol{\Lambda}_f]^T \frac{\partial \mathbf{R}}{\partial \mathbf{D}}$$

Adjoint-Based Optimization/Mesh Adaptation



- Current state-of-the-art: Integral of quadratic pressure deviation functional

$$f = \int_l \left(\frac{p - p_\infty}{p_\infty} \right)^2 dl.$$

- Near-field pressure waveform is a heuristic of ground loudness



RESULTS

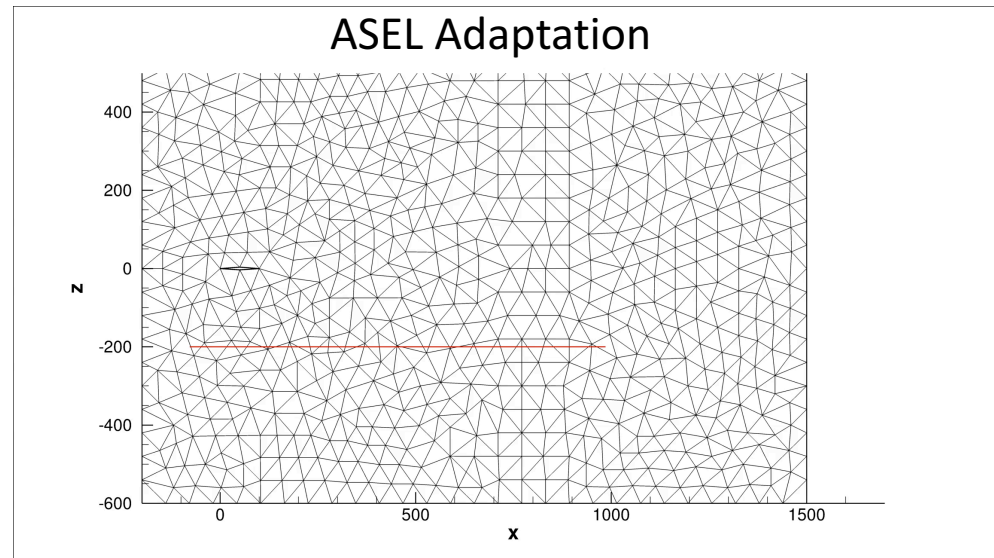
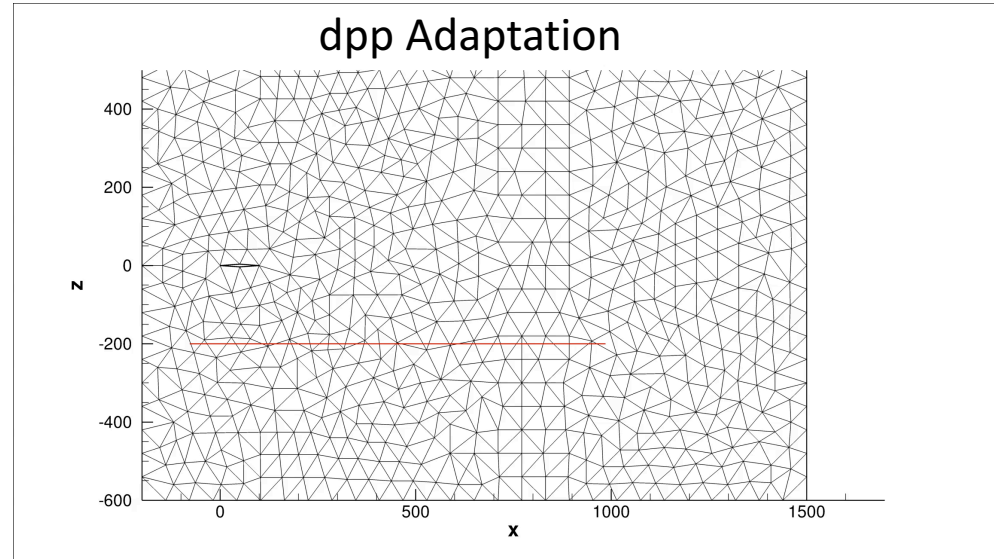
Case1: 2D Diamond Airfoil

- When enough mesh was provided, dpp adaptation and ASEL adaptation gave identical results

- Constraining the mesh to differentiate the schemes

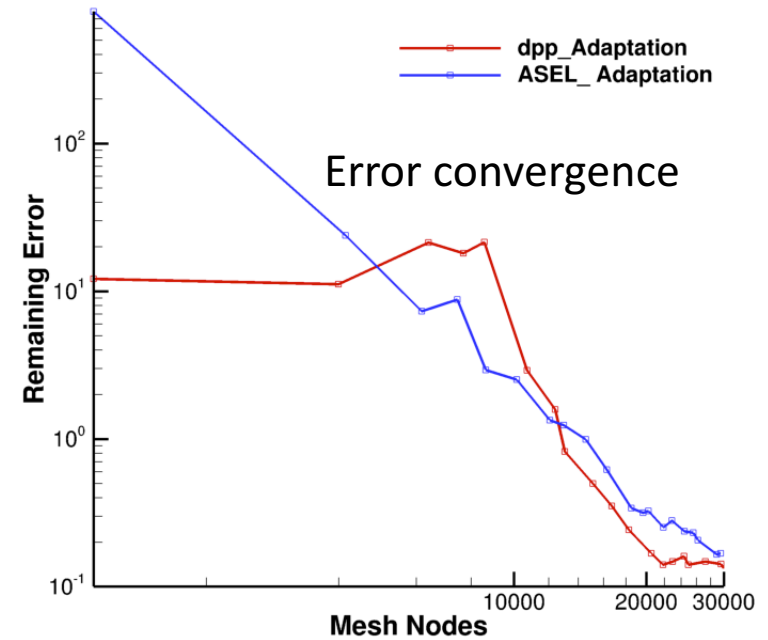
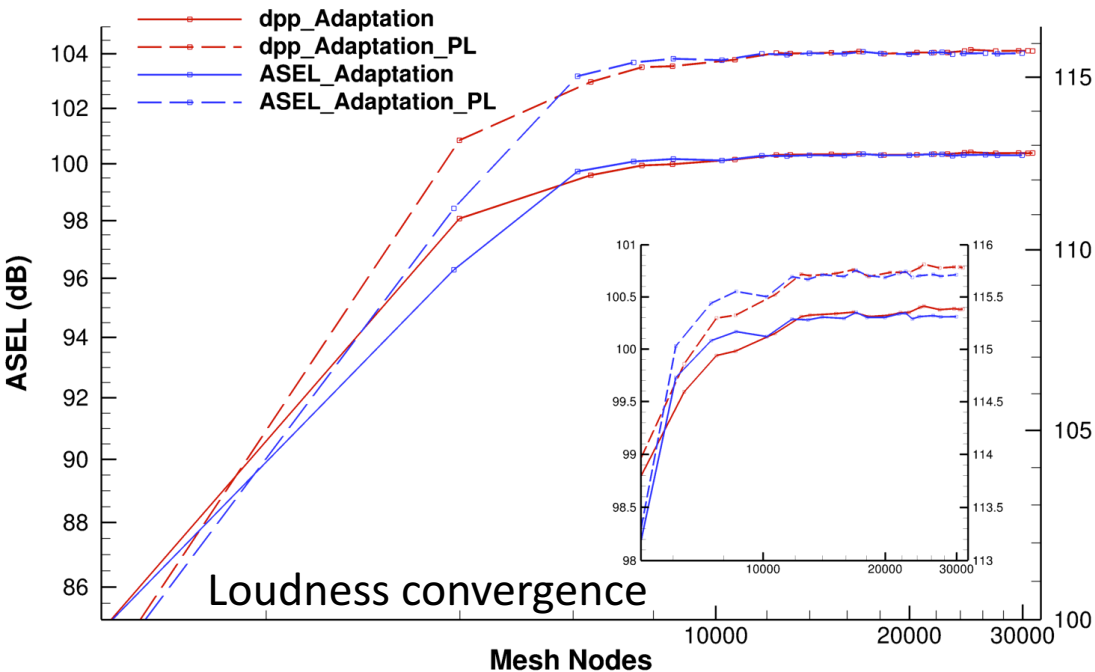
•Meshes

- More refinement in the wake for ASEL adaptation
- Regions above the geometry also refined in ASEL adaptation
- Refined farther into the domain with ASEL adaptation



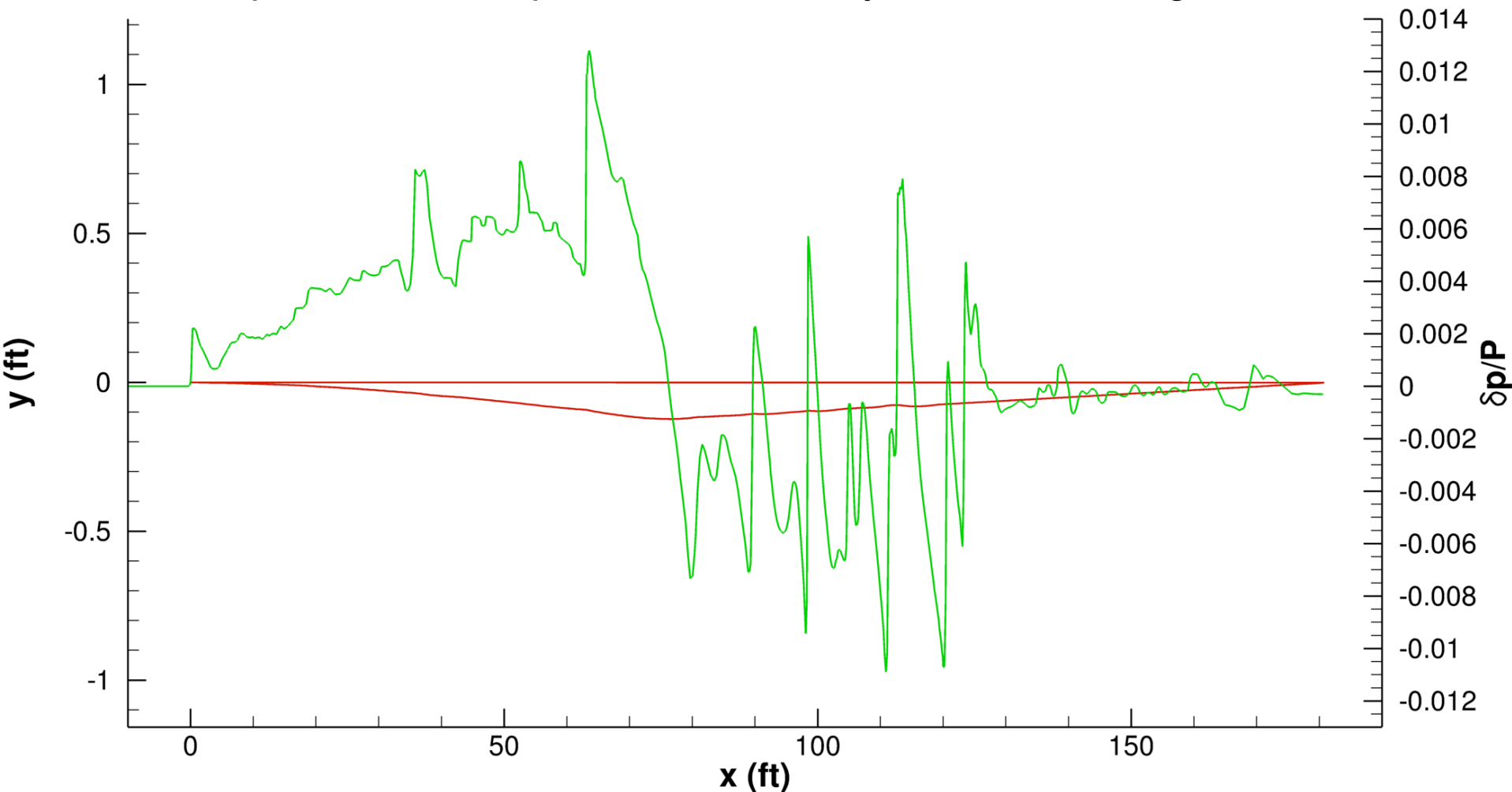
Case1: 2D Diamond Airfoil

- Remaining error drops three orders of magnitude for ASEL adaptation, and 2 orders for dpp
- Minor differences observed in loudness convergence



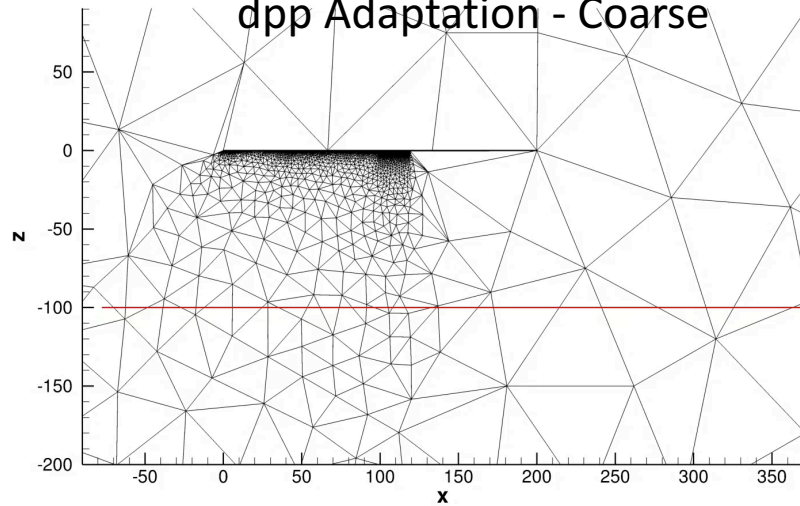
Case2: Airfoil with Complex Flow-field

- 2D case with a complex flow-field that can produce low boom
- Used supersonic small perturbation theory to inverse design airfoil

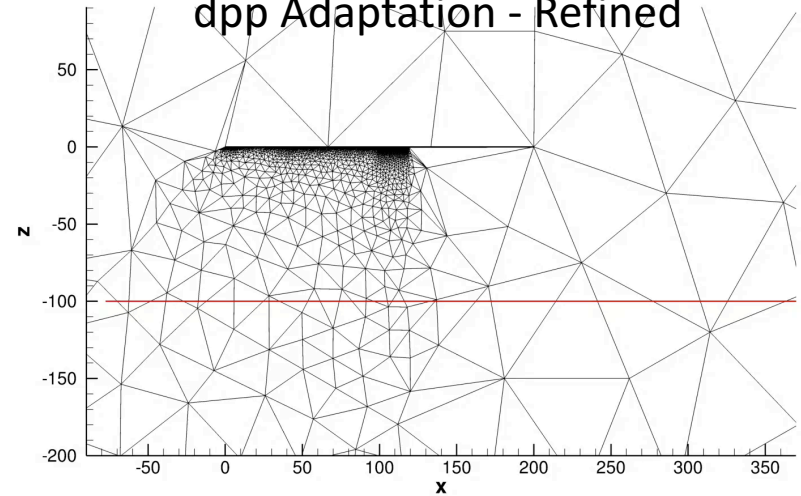


Case2: Effect of Mesh

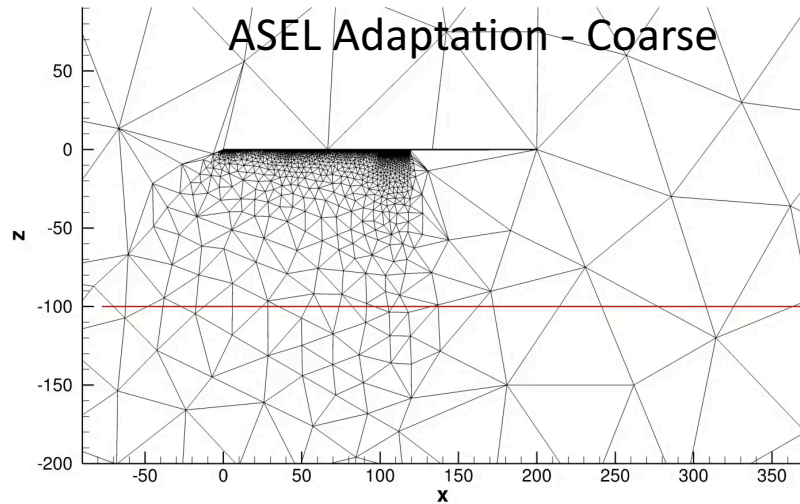
dpp Adaptation - Coarse



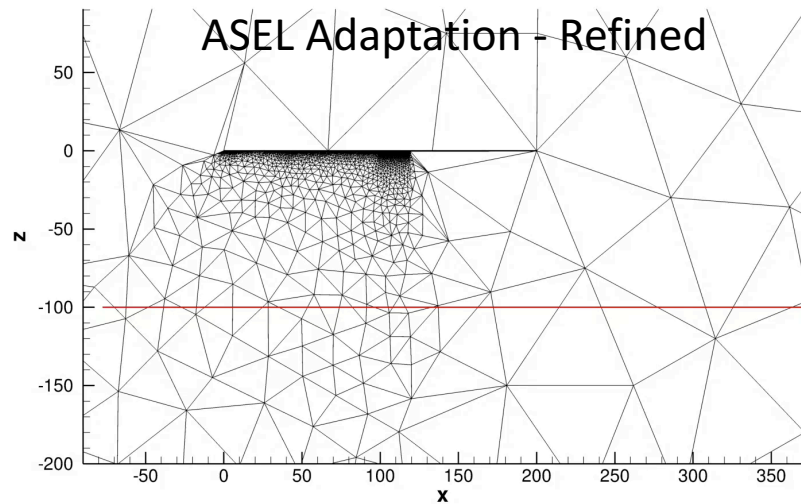
dpp Adaptation - Refined



ASEL Adaptation - Coarse

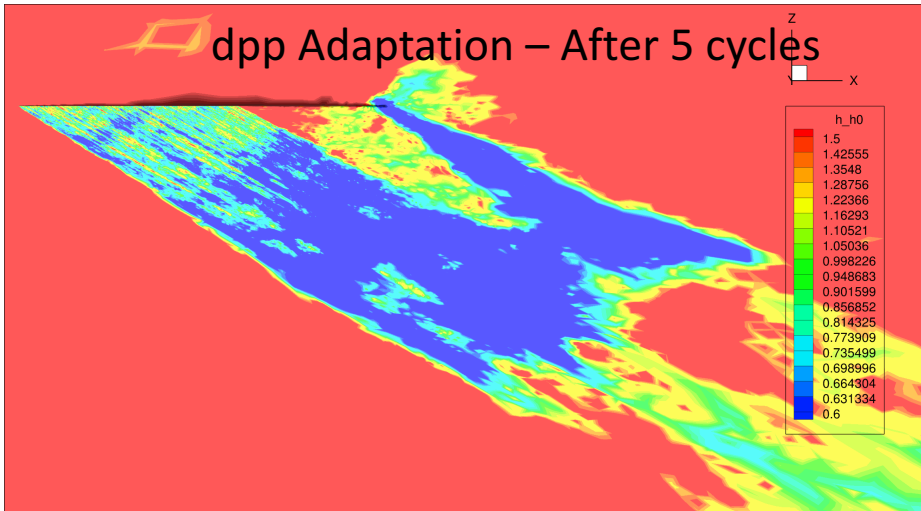


ASEL Adaptation - Refined

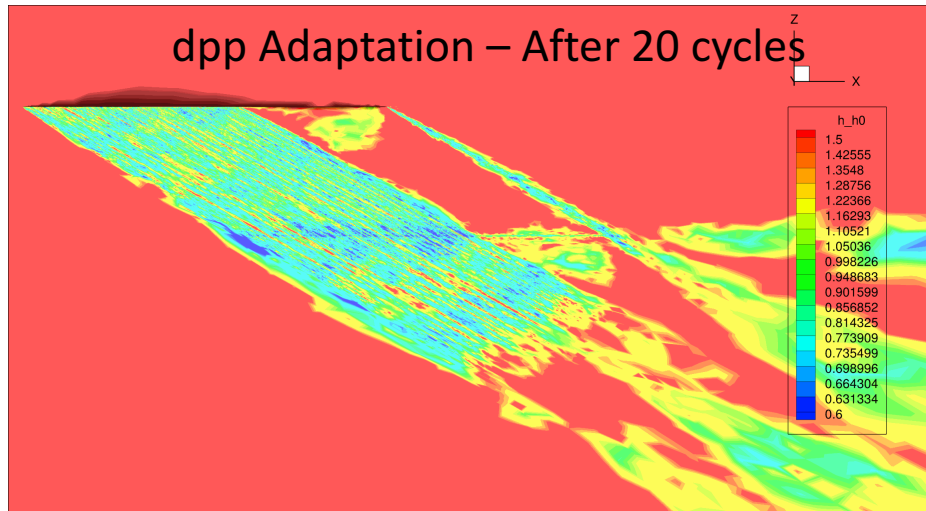


Case2: Cell Size Projection During Adaptation

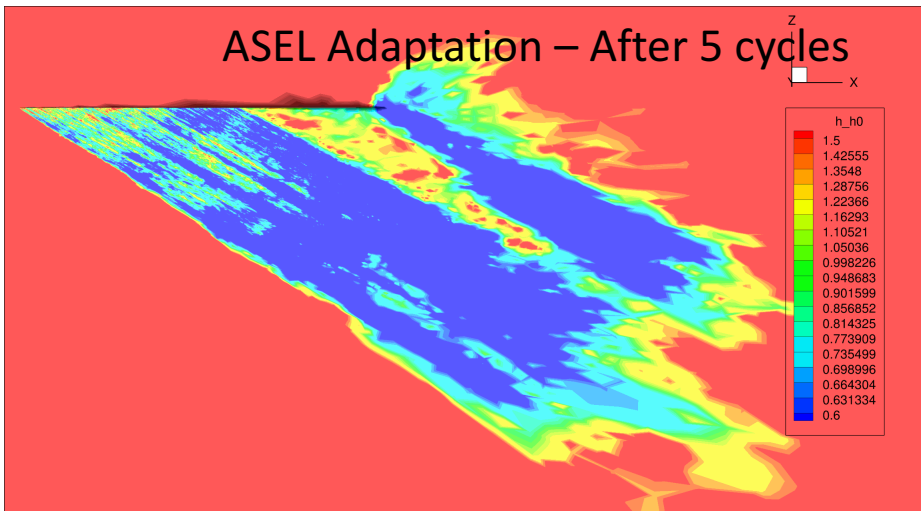
dpp Adaptation – After 5 cycles



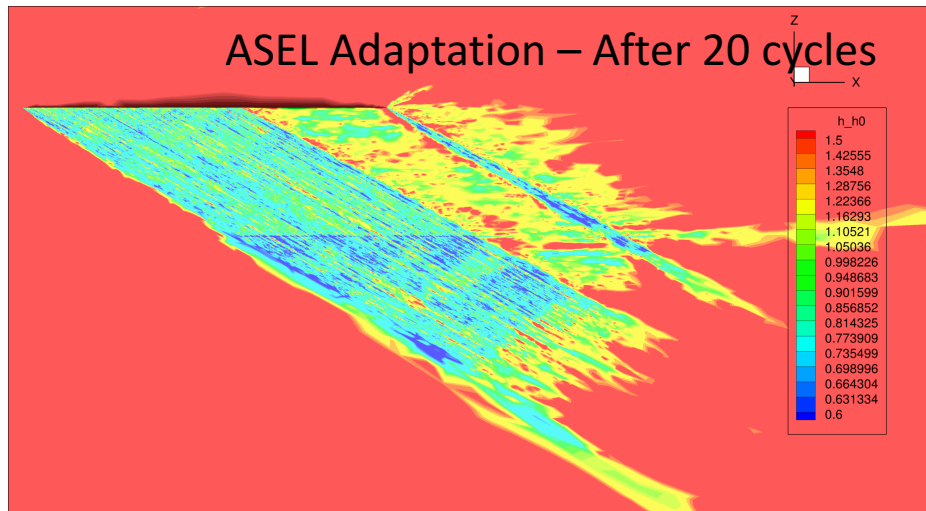
dpp Adaptation – After 20 cycles



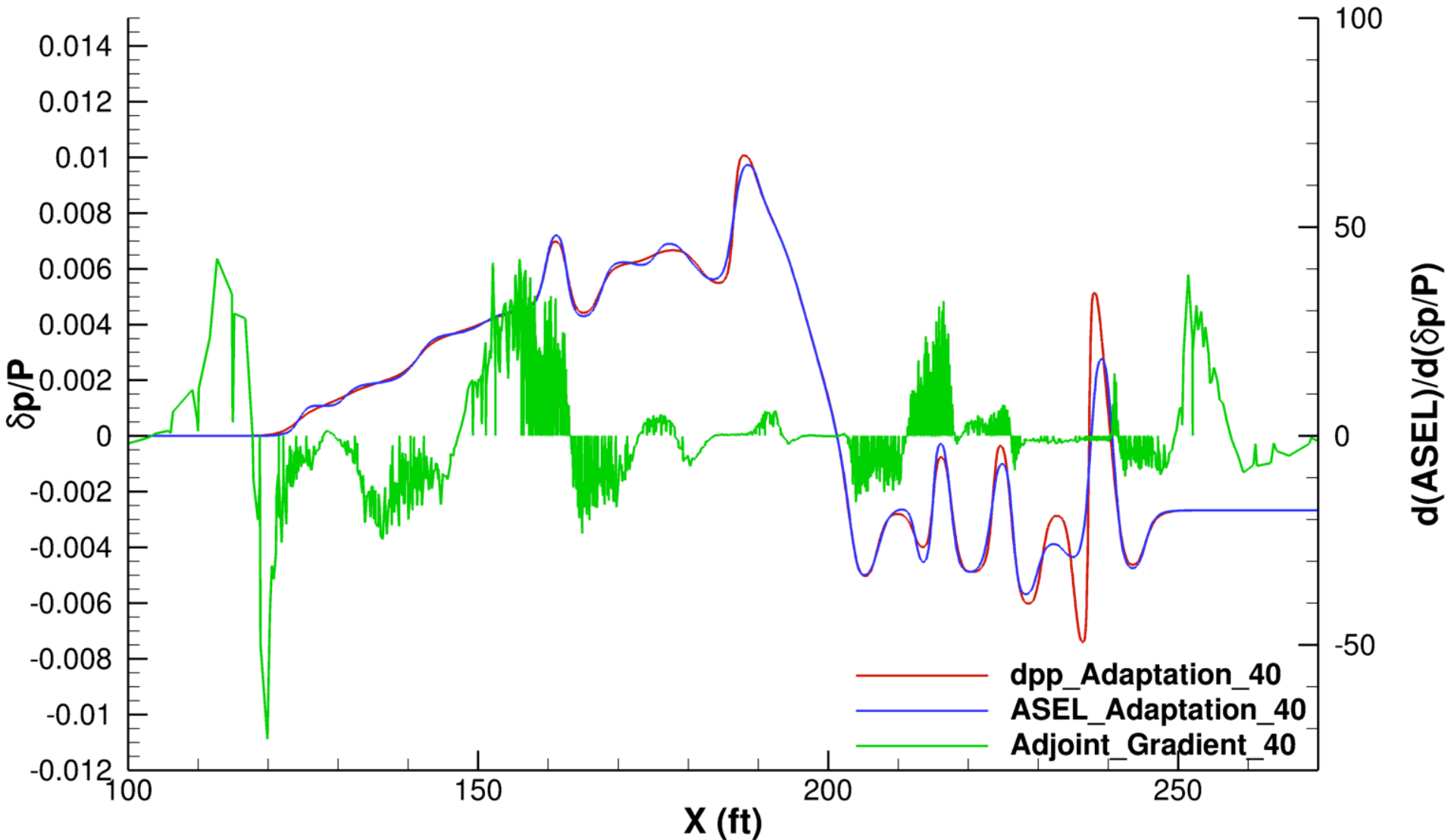
ASEL Adaptation – After 5 cycles



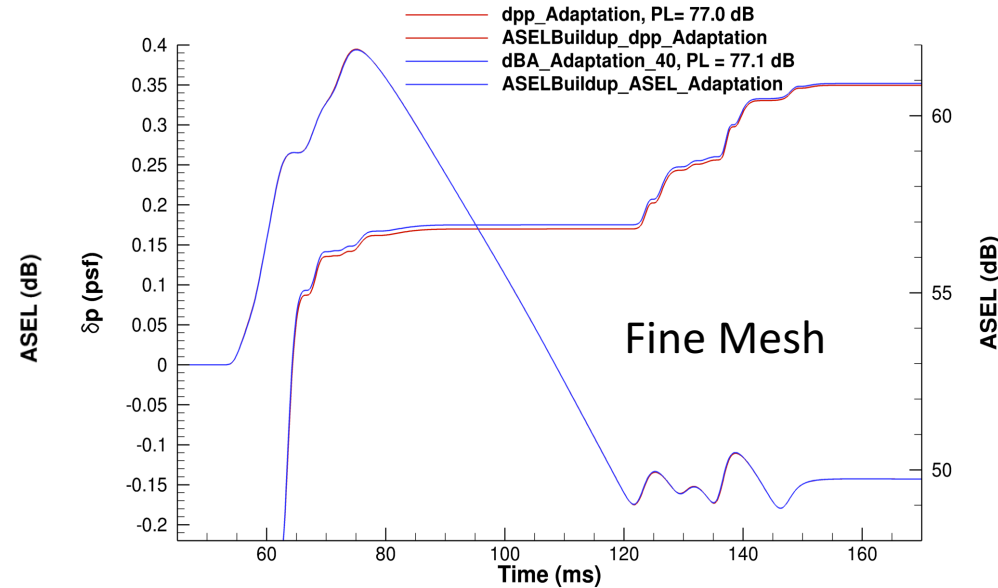
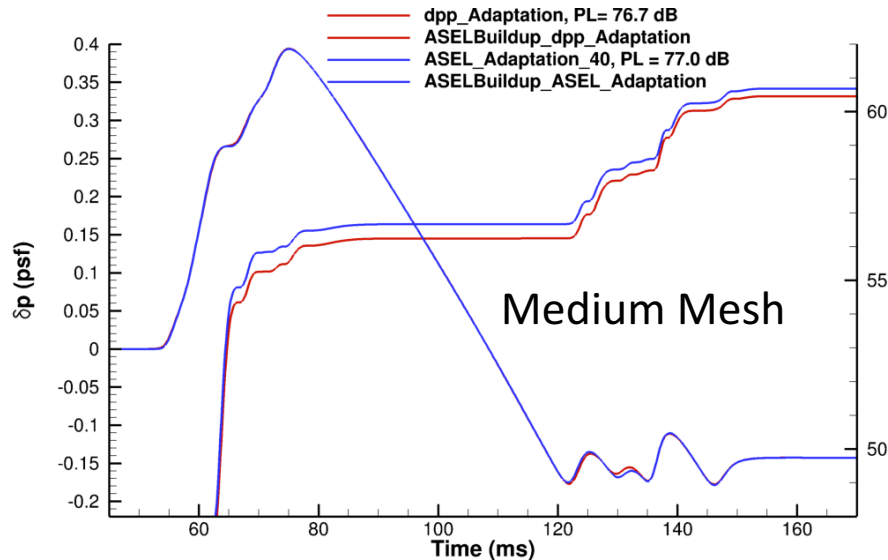
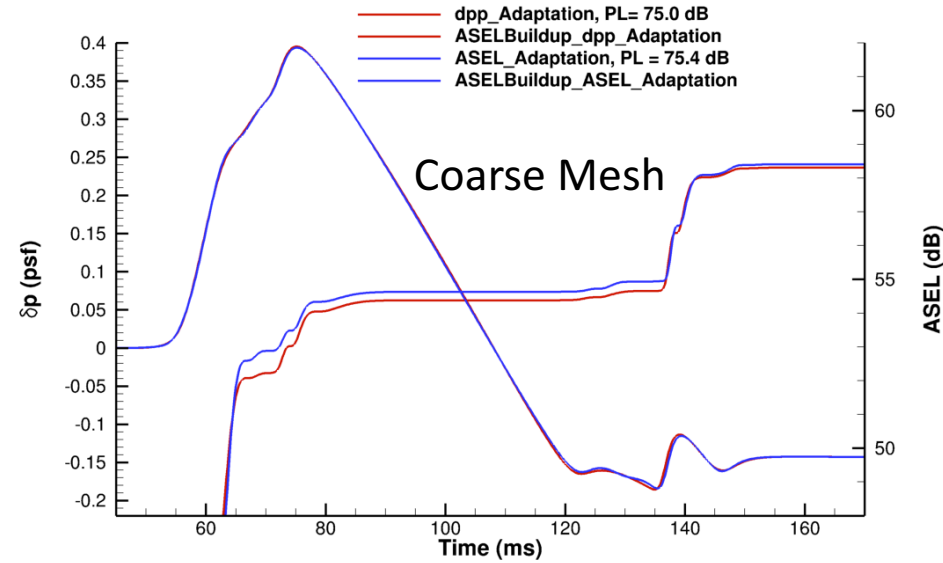
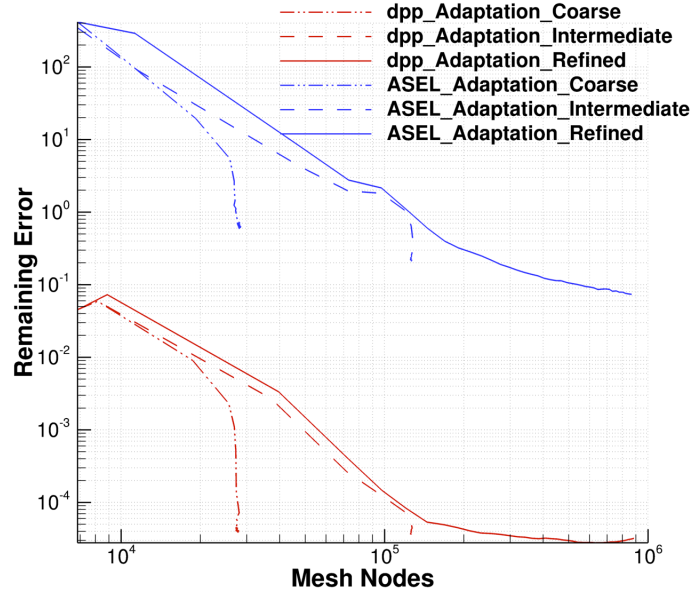
ASEL Adaptation – After 20 cycles



Case2: Moderate Mesh

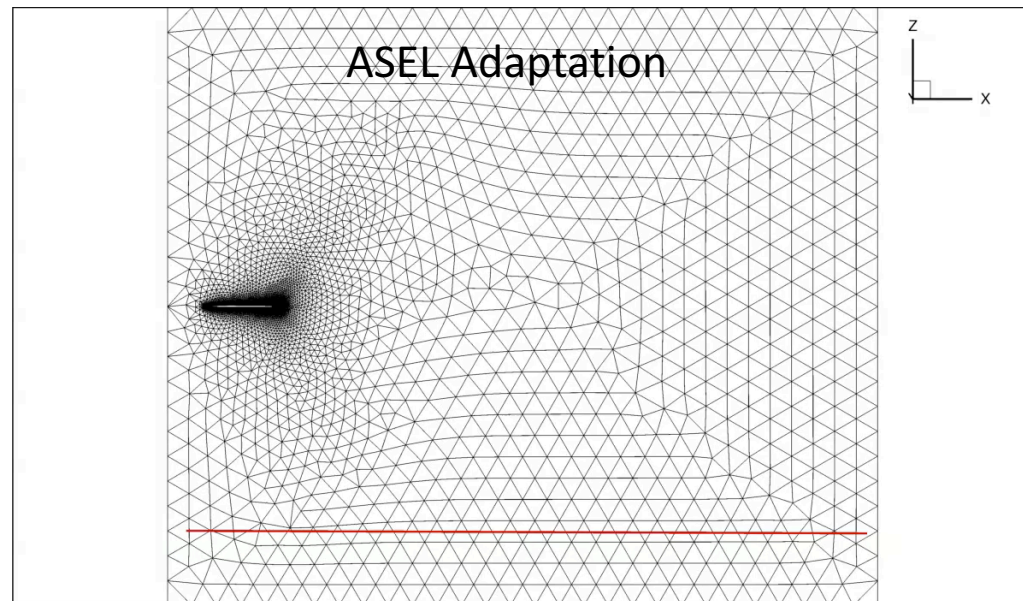
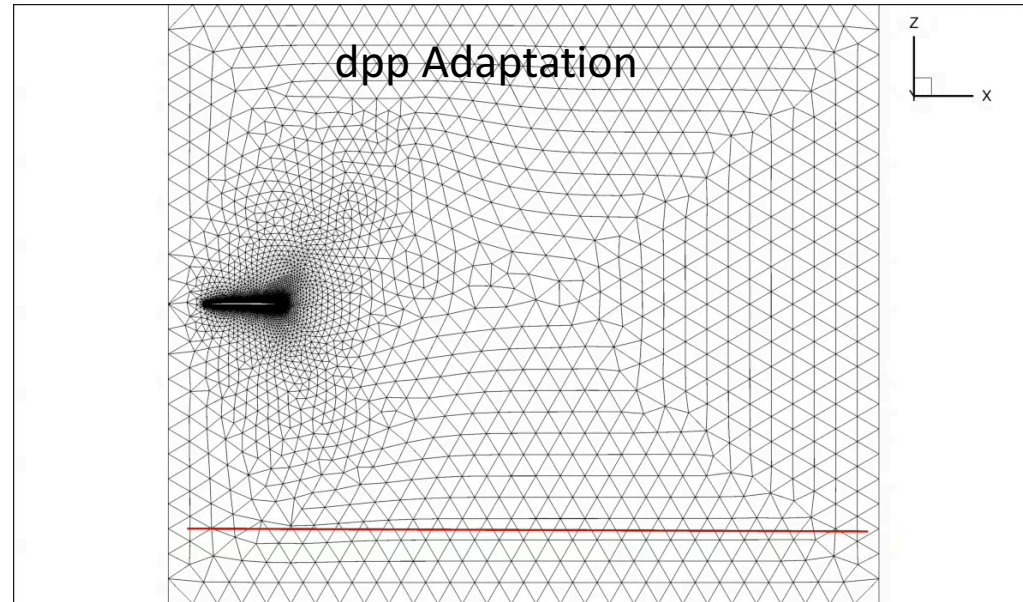


Case2: Error Convergence and Signatures



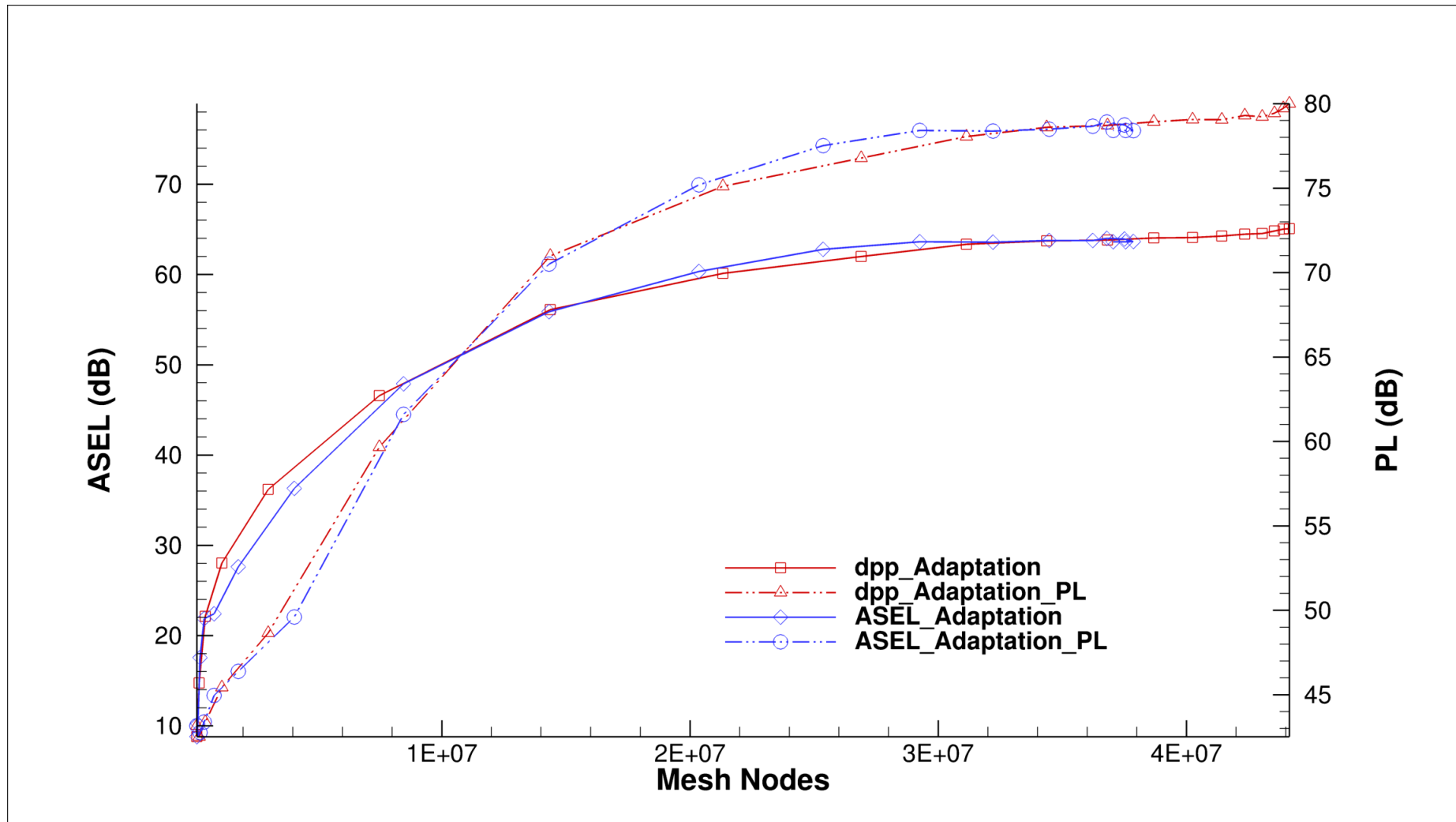
Case3: Axi-Symmetric Body of Revolution

- For a 3D case, the overall adaptation behavior is similar
 - Higher refinement in aft and above the body for dpp adaptation
 - Different from the 2D case before



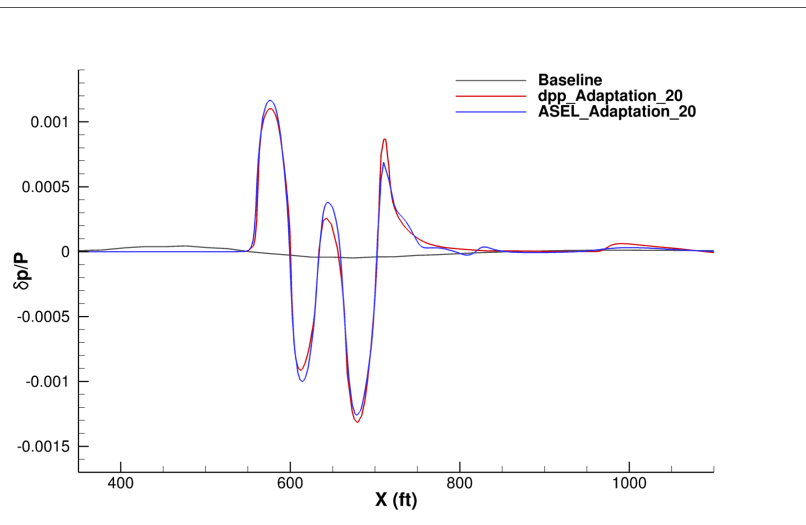
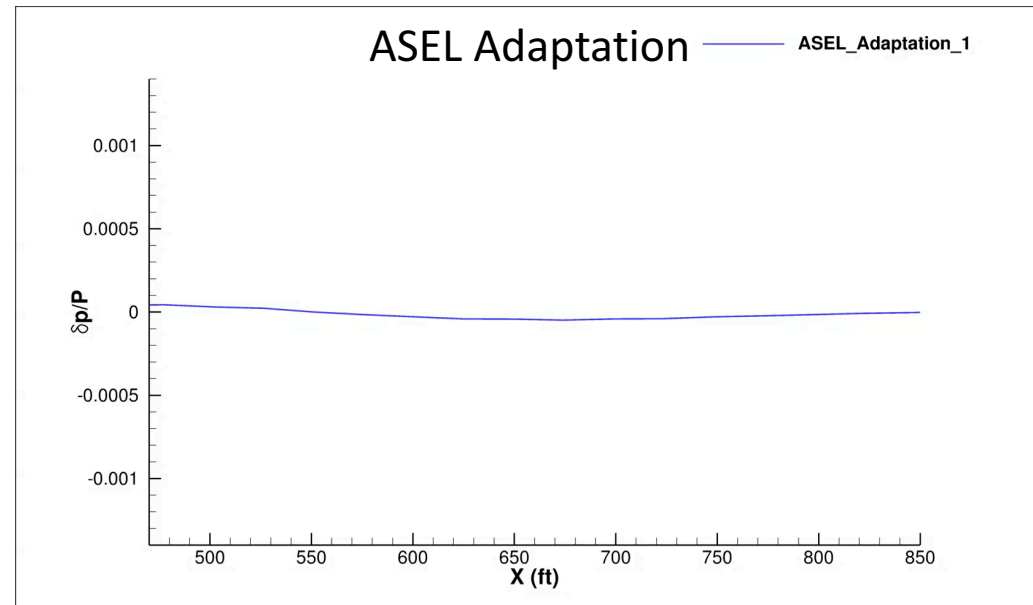
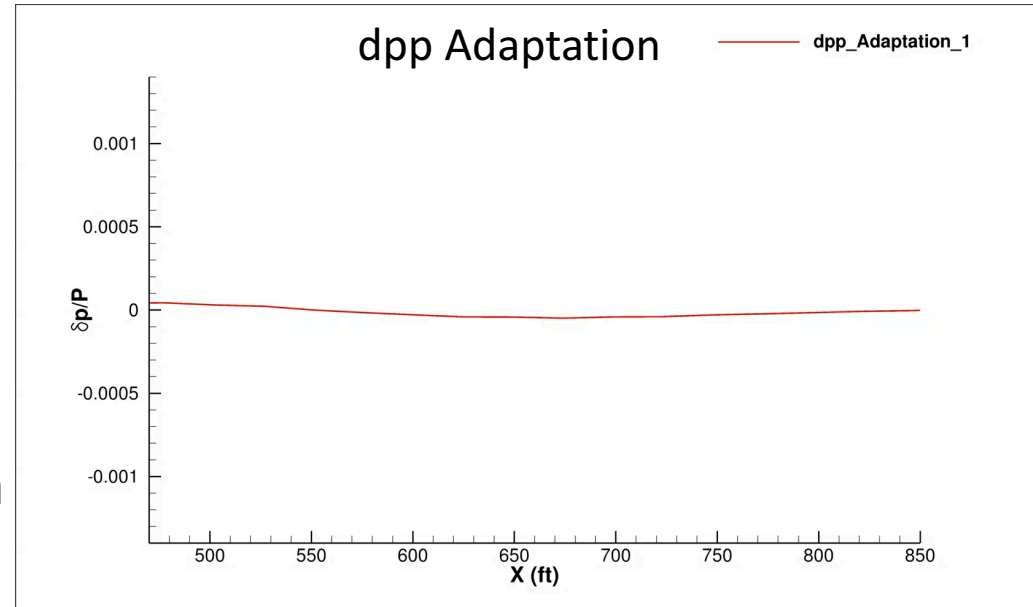
Case3: Axi-Symmetric Body of Revolution

- Loudness convergence is achieved earlier with smaller meshes for ASEL adaptation



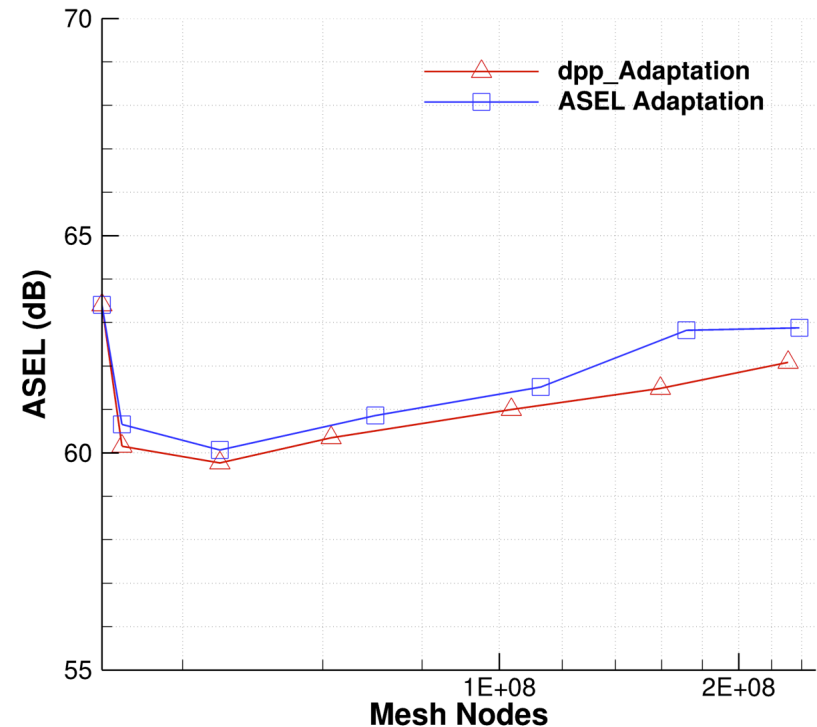
Case3: Axi-Symmetric Body of Revolution

- dpp adaptation picks up on shocks sooner than ASEL adaptation
- ASEL adaptation quickly “catches-up” to dpp adaptation
- First two shocks are better resolved using ASEL adaptation with smaller overall meshes



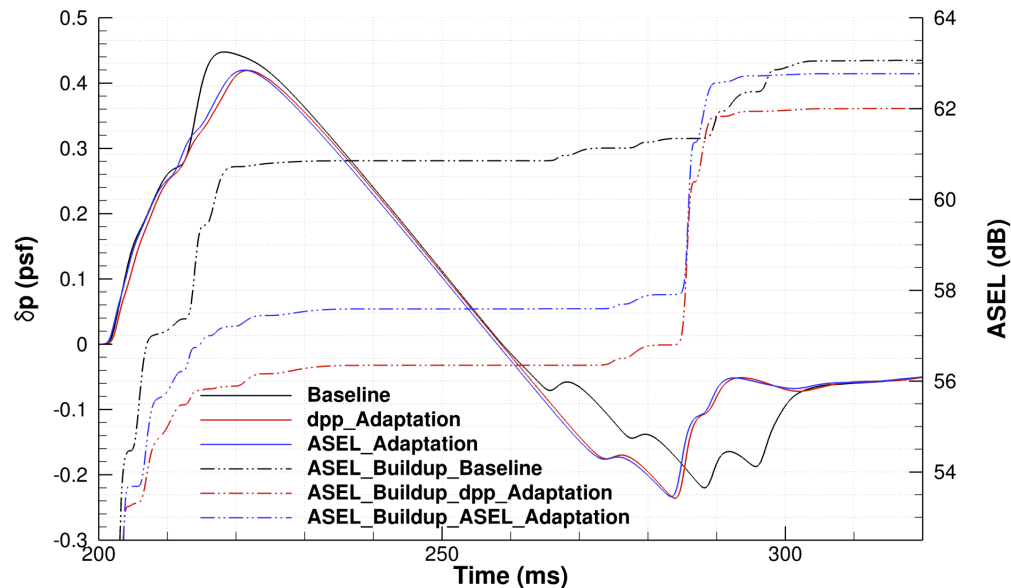
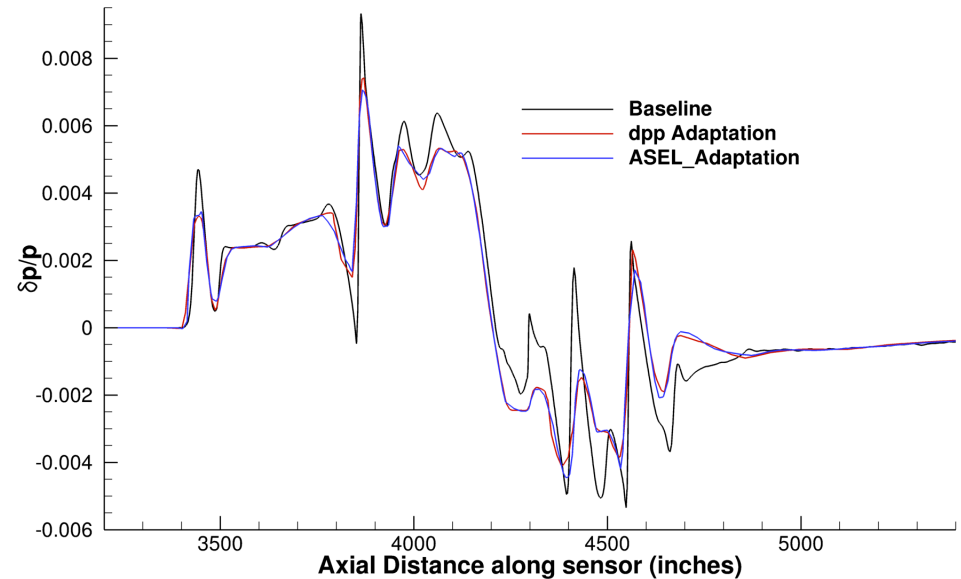
Case4: Low Boom Concept

- A low-boom demonstrator concept analyzed via mesh adaptation
- 8 adaptation cycles were run, to achieve loudness convergence
- ASEL from dp/p adaptation is within 0.5 dB, but not converged on the loudness scale
- With the same mesh growth guidance, ASEL adaptation has slightly larger mesh starting from adaptation cycle = 4
- Mesh size increased from 31M nodes to ~240M nodes



Case4: Low Boom Concept

- Differences observed in the near-field pressure waveform
- ASEL adaptation captures the smaller peaks better, while dp/p resolves the larger shocks crisply
- Ground signatures visually similar
- ASEL build-up shows steeper shocks of ASEL adaptation compared to dp/p adaptation
- Proximity of loudness from ASEL adaptation to baseline is fortuitous





Summary/Conclusions

- Demonstrated adjoint-based mesh adaptation for sonic boom loudness on multiple cases
- Current state-of-the-art for mesh adaptation is an off-body pressure functional, a heuristic or surrogate of low boom
- Using ASEL-based adaptation implicitly weighs regions of the pressure waveform based on their importance to loudness metrics
 - If detailed information is known of the underlying concept, dp/p adaptation may impose weights along the sensor accordingly
- More work is needed to show applicability in 3D simulations over realistic concepts
- ASEL adaptation may be used in conjunction with dp/p adaptation



Future Work

- Future Work
 - Leverage FUN3D development toward simultaneous mesh adaptation and design to generate suitable adapted meshes during design for minimizing sonic boom
 - During ASEL adaptation, sBOOM grid is fixed i.e. sBOOM does not contribute to the error to drive adaptation.
 - Enhance sBOOM to work with non-uniform grids and contribute towards adaptation error correction
 - Use ASEL sensitivities as weights to drive dp/p adaptation



Acknowledgments

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- Aeronautics Systems Analysis Branch (ASAB), NASA Langley
- Irian Ordaz – Initial gridding process using AFLR2/AFLR3 for 3D cases
- Michael Aftosmis for valuable feedback/suggestions

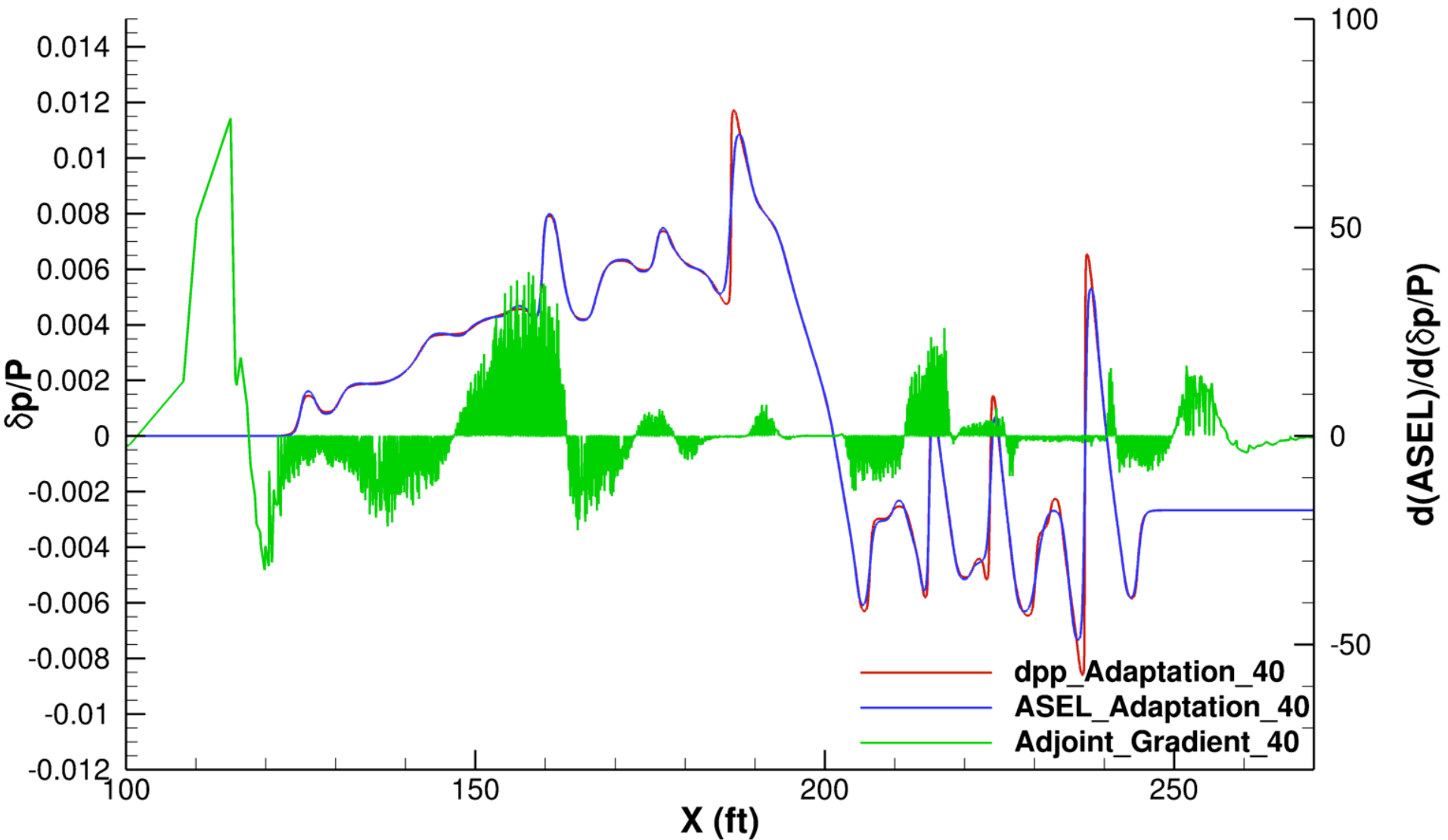
Questions?





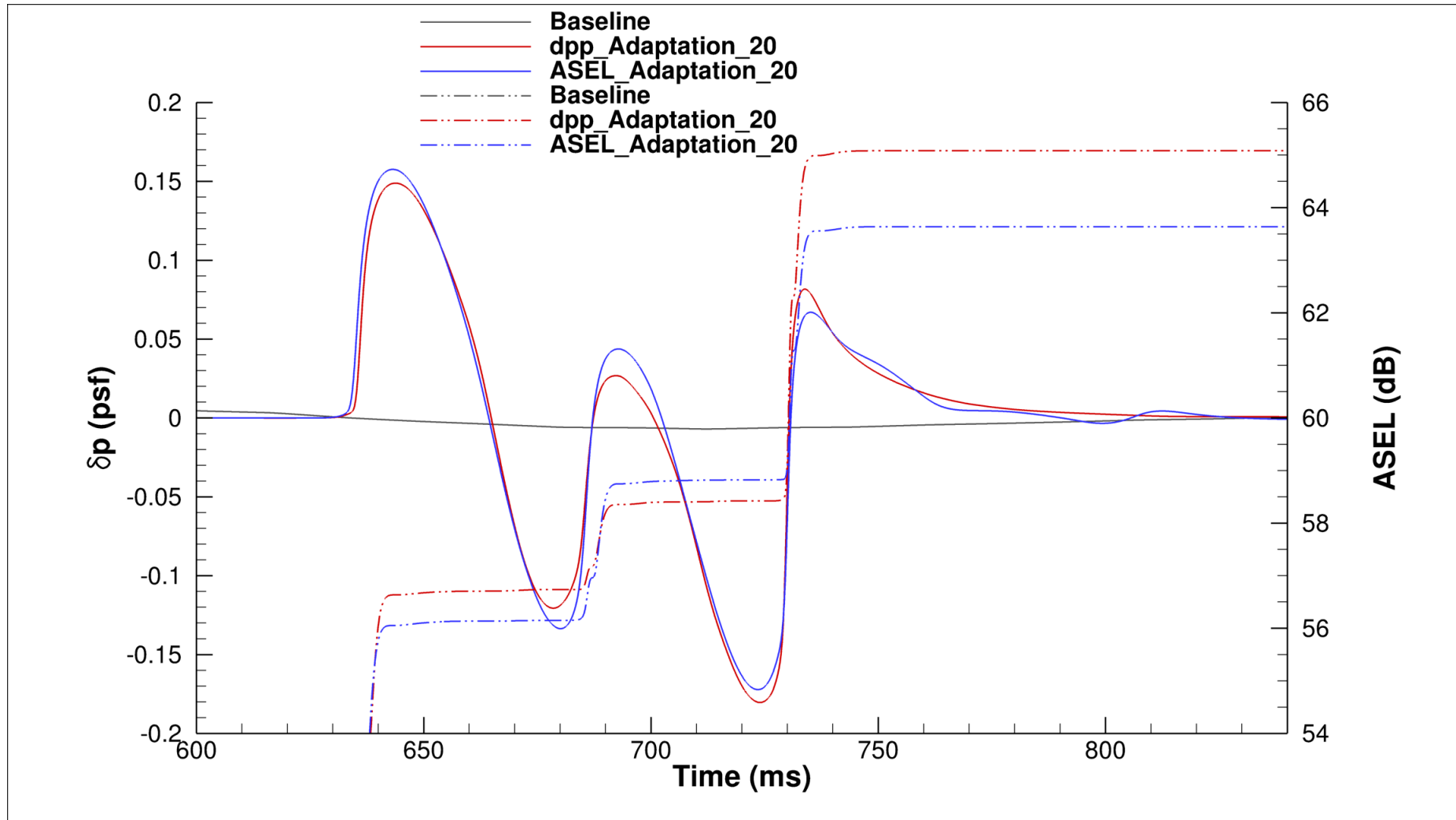
BACKUP-SLIDES

Case2: Refined Mesh



Case3: Axi-Symmetric Body of Revolution

- Result from ASEL adaptation has higher front loudness compared to dpp adaptation



Case3: Error Convergence

